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Spin Physics at J-PARC

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Spin-physics projects at J-PARC are explained by including future possibilities. J-PARC is the most-intense hadron-beam facility in the high-energy region above multi-GeV, and spin physics will be investigated by using secondary beams of kaons, pions, neutrinos, muons, and antiproton as well as the primary-beam proton. In particle physics, spin topics are on muon $g - 2$, muon and neutron electric dipole moments, and time-reversal violation experiment in a kaon decay. Here, we focus more on hadron-spin physics as for future projects. For example, generalized parton distributions (GPDs) could be investigated by using pion and proton beams, whereas they are studied by the virtual Compton scattering at lepton facilities. The GPDs are key quantities for determining the three-dimensional picture of hadrons and for finding the origin of the nucleon spin including partonic orbital-angular-momentum contributions. In addition, polarized parton distributions and various hadron spin topics should be possible by using the high-momentum beamline. The strangeness contribution to the nucleon spin could be also investigated in principle with the neutrino beam with a near detector facility.

Keywords: J-PARC, nucleon, spin, QCD, $g - 2$, electric dipole moment, kaon decay

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1. Introduction to J-PARC

Japan Proton Accelerator Research Complex (J-PARC) is located at Tokai in Japan,[1] and it is a joint facility between KEK (High Energy Accelerator Research Organization) and JAEA (Japan Atomic Energy Agency) for projects in wide fields of science. KEK is in charge of the particle- and nuclear-physics projects at the 50-GeV proton synchrotron. J-PARC provides most intense proton beam in the energy region above multi-GeV. Nuclear and particle physics projects use secondary beams such as kaons, pions, neutrinos, muons, and antiproton as well as the primary

50-GeV proton beam. The J-PARC experiments have been started for neutrino oscillations and strangeness hadron experiments. In this report, we explain spin physics at J-PARC, mainly on possibilities of hadron spin physics.

J-PARC could cover a wide range of spin projects from fundamental particle physics to hadron spin physics. They include muon $g-2$, muon and neutron electric dipole moments, and time-reversal violation experiment in a kaon decay as particle-physics projects. In hadron physics, there are possible projects for clarifying the origin of nucleon spin and associated three-dimensional structure of the nucleon.

J-PARC facility

A bird's-eye view of the J-PARC facility is shown in Fig. 1. The accelerator consists of a linac as an injector, a 3-GeV rapid cycling synchrotron, and a 50-GeV synchrotron. The energy of the 50-GeV synchrotron is 30 GeV at this stage. J-PARC provides most intense proton beam in the high-energy region ($E > 1$ GeV), and it is 1 MW in the 3-GeV synchrotron and 0.75 MW is expected in the 50-GeV one. There are three major projects at J-PARC:

- material and life sciences as well as particle physics with neutrons and muons produced by the 3-GeV proton beam,
- nuclear and particle physics with secondary beams (pions, kaons, neutrinos, muons, and antiprotons) by the 50-GeV proton beam and also with protons of the 50-GeV primary beam,
- nuclear transmutation and neutron physics by the linac.

Hadron-physics projects are investigated at the hadron experimental facility in Fig. 1. Experiments on lepton-flavor violation and time-reversal violation experiment in a kaon decay will be done also in this hadron hall, in which the beam-layout plan is shown in Fig. 2. The K1.8 is intended to have kaons with momentum around 1.8 GeV/c for the studies, for example, on strangeness -2 hypernuclei with Ξ^- by (K^-, K^+) reactions. The K1.1/0.8 beamline is designed for low-momentum stopped kaon experiments such as the studies of kaonic nuclei. The neutral kaon beamline (KL) is for studying CP violating processes such as $K_L \to \pi^0 \nu \bar{\nu}$. The "High p" in Fig. 2 indicates the high-momentum beamline for 50-GeV protons and unseparated hadrons. In the beginning stage of J-PARC, the proton-beam energy is 30 GeV
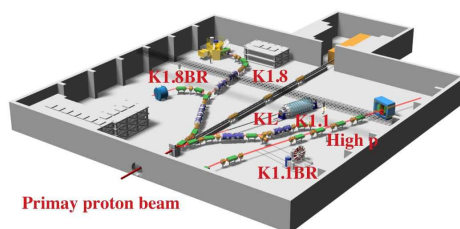

Fig. 1.   J-PARC facility.[1]

Fig. 2.   Beamline layout of hadron hall.[1]

instead of the original plan of 50 GeV. Measurements on muon $g - 2$, muon and neutron electric dipole moment will be done at the Materials and Life Science Experimental Facility (MLF) and at the linac part for neutron physics. Furthermore, hadron spin physics could be possible in principle with the neutrino beam with a near detector, for example, by focusing on strangeness spin in the axial form factor.

In future, hadron spin projects will become possible at the hadron hall because the high-momentum beamline in Fig. 2 will be ready in the Japanese fiscal year of 2016. The high-momentum beamline can transport the primary proton beam (30 GeV) with the intensity of 10^{10}-10^{12}/sec to the Hadron Hall, and it is a branch from the main proton beam of 10^{13} or 10^{14}/sec. In addition, we can obtain unseparated secondary beams such as pions etc. The beam intensity of these secondaries depends on its species and momentum. A typical intensity for 10 GeV/c (15 GeV/c) pions would be in the order of 10^{7}/sec (10^{6}/sec). Because there is no approved proposal to study hadron spin physics at J-PARC at this stage, we need to develop such possibilities. In this article, we first introduce particle-spin projects, and then we focus our discussions on high-energy hadron projects.

2. Spin in particle physics

Particle-spin projects are intended to probe physics beyond the standard model. Here, we introduce three projects on (1) muon $g - 2$ and electric dipole moment, (2) muon polarization in kaon decay, and (3) electric dipole moment of the neutron.

2.1. *Muon $g - 2$ and electric dipole moment*

There is a project to measure the anomalous magnetic moment $(g - 2)$ and electric dipole moment (EDM) of the muon at the MLF of J-PARC.[2] There is a long history of measurements on the muon $g - 2$. The muon magnetic moment is given by its spin and gyromagnetic ratio g_μ as $\vec{\mu}_\mu = g_\mu \frac{e}{2m} \vec{s}$. The anomalous magnetic moment a_μ is related to $g_\mu - 2$ as $a_\mu = (g_\mu - 2)/2$. We denote the muon EDM as d_μ. The electric dipole moment is given by the spin and η_μ as $\vec{d}_\mu = \eta_\mu \frac{e\hbar}{2m} \vec{s}$. The most recent measurements were done by the BNL-E821 experiment, and a_μ was measured down to 0.54 ppm and d_μ to 1.9×10^{-19}e·cm.[2] It is especially interesting that the current value $a_\mu = 0.00116592089(63)$ deviates from the theoretical value $0.00116591828(49)$ with 3.3σ discrepancy. This deviation exists even if theoretical uncertainties, mainly from hadronic corrections, are taken into account, so that it could suggest new physics. Therefore, it is important to improve the experimental measurement by an independent method.

Under the static electric and magnetic fields, the muon spin precesses with the frequency

$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] - \frac{e}{m} \left[\frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right] \equiv \vec{\omega}_a + \vec{\omega}_\eta, \quad (1)$$

where $\vec{\omega}_a$ is the precession vector due to the anomalous magnetic moment, and $\vec{\omega}_\eta$ is the one due to the electric dipole moment. In the CERN and BNL experiments, the

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muon energy was chosen to terminate the contribution of the $\vec{\beta} \times \vec{E}$ term, and the EDM contribution $\vec{\omega}_\eta$ is neglected. In the proposed J-PARC experiment in Fig. 3, the electric field $\vec{E}$ is terminated to give the precession frequency

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\vec{\beta} \times \vec{B}\right]. \tag{2}$$

Here, the first $g-2$ term and the second EDM term are orthogonal with each other, and they can be separated by appropriate experimental design. The purpose of this experiment is to improve the current limit of $g-2$ to 0.1 ppm by a factor of five and the EDM to 10^{-21} e·cm by a factor of two orders of magnitude than the current limit. R&D is in progress for significant technological developments to start this experiment within 2010's.[2]
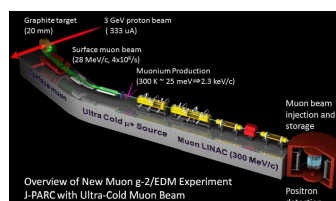

Fig. 3. $g-2$ and EDM experiment.[2]

2.2. *Transverse muon polarization in kaon decay*

There is a project to investigate time-reversal violation by the transverse muon polarization $P_T = \hat{s}_\mu \cdot (\hat{p}_{\mu^+} \times \hat{p}_{\pi^0})$ in kaon decay $K^+ \to \pi^0 \mu^+ \nu$ at J-PARC.[3] It is called TREK (Time-Reversal violation Experiment with Kaons) experiment. This polarization could probe a signature beyond the standard model because the standard-model contributions from higher-order effects are considered to less than 10^{-6}. The most recent measurement was done by the KEK-E246 experiment and it was $P_T = -0.0017 \pm 0.0023\,(\text{stat}) \pm 0.0017\,(\text{syst})$, which is consistent with no T-violation. New-physics models suggest that the polarization value should be as large as 10^{-3}, which is just below the KEK-E246 limit. Therefore, it is valuable to measure the polarization more accurately to provide a clue for new physics. In the proposed J-PARC experiment, background reduction will be done by improved detector, especially the upgrade of polarimeter and magnet. The resulting error is expected to be $\delta P_T = 10^{-4}$. In the beginning low-intensity period of J-PARC, the collaboration proposed to start another experiment E36 on the decay ratio $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ to test lepton universality by using a subsystem of the TREK experiment.[3]

2.3. *Electric dipole moment of the neutron*

Ultracold neutrons (UCN) are used for measurements of fundamental physics quantities, and new generation UCN sources are under developments for experiments at facilities including J-PARC.[4] In particular, the neutron electric dipole moment (nEDM) should be able to probe new physics. For example, the supersymmetric model indicates that the nEDM is of the order of 10^{-27} e·cm, which is just below the limit 3×10^{-26} e·cm obtained by a Grenoble experiment. Since the limit is constrained by the statistical error, efforts have been made to increase the UCN density,

as well as efforts to reduce the systematic error. Spallation UCN sources are considered for the nEDM measurement at J-PARC. Due to the increase of the proton-beam power to 20 kW, the density is expected to become 10^3-10^4 UCN/cm^3, whereas it was 0.7 UCN/cm^3 in the Grenoble experiment. With the new UCN sources together with the intense proton beam, much improvement will be made for the upper bound of the nEDM into the region of 10^{-28} e·cm. At J-PARC, the nEDM experiment is considered at the linac section.[4]

3. Spin in hadron physics

3.1. *Flavor dependence of antiquark distributions*

There are proposals on dimuon experiments by using primary proton beam for measuring parton distribution functions (PDFs) in the medium Bjorken-x region.[5] A typical example is shown in Fig. 4 for measuring the light-antiquark distribution ratio $\bar{d}(x)/\bar{u}(x)$ by the Drell-Yan processes of pp and pd, where p (d) is proton (deuteron). According to perturbative QCD, the $\bar{u}/\bar{d}$ asymmetry should be very small. Experimentally, the difference was sug-

Fig. 4.   Drell-Yan cross-section ratios.[5]

gested by the violation of the Gottfried sum rule,[6] and it was confirmed explicitly by the Fermilab-E866 measurements in Fig. 4. However, there is a peculiar tendency of $\bar{d}/\bar{u} < 1$ as x becomes larger, which is difficult to be understood theoretically. The E906/SeaQuest experiment at Fermilab is in progress for dimuon experiments to test this tendency, and it could be continued at J-PARC.
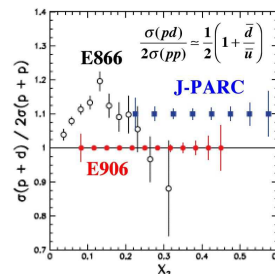
Measurements of antiquark distributions in nuclei are also interesting. The Fermilab Drell-Yan measurements showed that nuclear modifications of the antiquark distributions are very small at $x \sim 0.1$, which is in contradiction to the conventional pion-excess contribution. It is important to confirm this result by an independent experiment and to extend the measured x region for finding a physics mechanism of nuclear medium effects on the antiquark distributions. In addition, determination of parton distribution functions (PDFs) at large x is valuable for precisely calculating other high-energy reactions, for example, high-p_T jet and hadron production cross sections at LHC.

3.2. *Generalized parton distributions*

Generalized parton distributions (GPDs) are key quantities for studying three-dimensional structure of hadrons, and hence to clarify the origin of the nucleon spin including partonic orbital-angular-momentum contributions.[7] They are measured typically in deeply virtual Compton scattering (DVCS) as shown in Fig. 5. However, there are possibilities
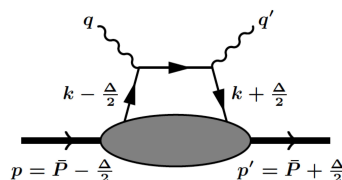

Fig. 5.   Kinematics for GPDs.

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to investigate them at hadron facilities like J-PARC.

First, we define kinematical variables for the process $\gamma^* + p \to \gamma + p$ by the momenta given in Fig. 5. The average nucleon and photon momenta ($\bar{P}$ and $\bar{q}$) and the momentum transfer Δ are defined by $\bar{P} = (p+p')/2$, $\bar{q} = (q+q')/2$, $\Delta = p'-p = q-q'$. Then, Q^2 and t are given by $Q^2 = -q^2$, $\bar{Q}^2 = -\bar{q}^2$, $t = \Delta^2$, and the generalized scaling variable x and a skewdness parameter ξ are defined by $x = Q^2/(2p \cdot q)$, $\xi = \bar{Q}^2/(2\bar{P} \cdot \bar{q})$. The variable x indicates the lightcone momentum fraction carried by a quark in the nucleon. The skewdness parameter ξ or the momentum Δ indicates the momentum transfer from the initial nucleon to the final one or the one between the quarks. The GPDs for the nucleon are given by off-forward matrix elements of quark and gluon operators with a lightcone separation between nucleonic states. The quark GPDs are defined by

$$\int \frac{dy^-}{4\pi} e^{ix\bar{P}^+ y^-} \left\langle p' \left| \overline{\psi}(-y/2)\gamma^+ \psi(y/2) \right| p \right\rangle \Big|_{y^+ = \vec{y}_\perp = 0}$$
$$= \frac{1}{2\bar{P}^+} \overline{u}(p') \left[H_q(x,\xi,t)\gamma^+ + E_q(x,\xi,t)\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M} \right] u(p), \qquad (3)$$

where $H_q(x,\xi,t)$ and $E_q(x,\xi,t)$ are the unpolarized GPDs for the nucleon.

The major properties of the GPDs are the following. In the forward limit ($\Delta, \xi, t \to 0$), the nucleonic GPDs $H_q(x,\xi,t)$ become usual PDFs: $H_q(x,0,0) = q(x)$. Next, their first moments are the Dirac and Pauli form factors of the nucleon: $\int_{-1}^{1} dx H_q(x,\xi,t) = F_1(t)$, $\int_{-1}^{1} dx E_q(x,\xi,t) = F_2(t)$. Furthermore, the second moment is related to the quark orbital-angular-momentum contribution (L_q) to the nucleon spin: $J_q = \frac{1}{2} \int dx\, x \left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0) \right] = \frac{1}{2}\Delta q + L_q$. From this relation, we expect that the origin of nucleon spin will be clarified by including the orbital-angular-momentum contributions. The GPDs contain information on the longitudinal momentum distributions and transverse structure as the form factors, so that they are appropriate quantities for understanding the three-dimensional structure of hadrons. The GPDs can be measured by the virtual Compton scattering in Fig. 5 at lepton facilities. However, they can be measured also at hadron facilities such as J-PARC and GSI-FAIR, and examples are explained in the following subsections.

3.2.1. *Exclusive Drell-Yan for studying GPDs*

The unseparated hadron beam, which is essentially the pion beam, will become available at the high-momentum beamline of J-PARC, so the exclusive Drell-Yan process is a possible future project at J-PARC. In Fig. 6, the exclusive dimuon process $\pi^- + p \to \mu^+\mu^- + B$ is shown.[8] The process probes the nucleonic GPDs if B is the nucleon, whereas it is related to the transi-

Fig. 6.   Exclusive Drell-Yan.
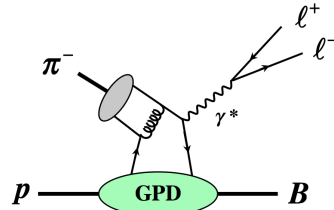
tion GPDs for $B \neq N$. The cross section contains not only the GPDs but also the

pion distribution amplitude. Although there are models for this quantity such as the asymptotic form or the Chernyak-Zhitnitsky type, the pion part is rather well studied and tested experimentally by the $\gamma\pi$ transition of Belle and BaBar. Using such studies for constraining the pion distribution amplitude, we should be able to obtain information on the GPDs by the exclusive Drell-Yan process.

3.2.2. *GPDs in the ERBL region*

Using the high-energy proton beam, we could investigate the GPDs at hadron facilities by using exclusive hadron-production reactions $a + b \to c + d + e$ such as $N + N \to N + \pi + B$, as shown in Fig. 7.[9] The GPD has three kinematical regions, (1) $-1 < x < -\xi$, (2) $-\xi < x < \xi$, (3) $\xi < x < 1$, as shown in Fig. 8. The intermediate region (2) indicates an emission of quark with momentum fraction $x + \xi$ with an emission of antiquark with momentum fraction $\xi - x$. The regions (1) and (3) are called as DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) regions, and (2) is called the ERBL (Efremov-Radyushkin-Brodsky-Lepage) region. If the hadrons c and d have large and nearly opposite transverse momenta and a large invariant energy, so that an intermediate exchange could be considered as a $q\bar{q}$ state. Then, the $q\bar{q}$ attached to the nucleon is expressed by the GPDs in a special kinematical region of the ERBL which is in the middle of three regions of Fig. 8. This method of measuring the GPDs is complementary to the virtual Compton scattering in the sense that the specific ERBL region is investigated in the medium x region due to the J-PARC energy of 30 GeV.
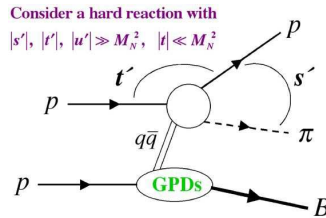

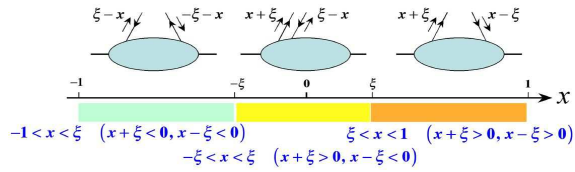Fig. 7.   GPD studies in $2 \to 3$ process.[9]

Fig. 8.   Three kinematical regions of GPDs.

3.3. *Transverse-momentum-dependent distributions*

In order to understand the origin of nucleon spin including orbital angular momenta, it becomes necessary to understand the three-dimensional structure of the nucleon. The momentum distribution along the motion of the nucleon is the longitudinal parton distribution function, and the transverse distribution plays a role of form factor at given x. The inclusive Drell-Yan $(p + p \to \mu^+\mu^- + X)$ measurements can probe transverse-momentum-dependent (TMD) polarized parton distributions, so called Boer-Mulders (BM) functions, by observing violation of the Lam-Tung relation in the cross sections.[5] The BM functions indicate transversely-polarized quark distributions in the unpolarized nucleon.

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Other interesting TMD distributions are the Sivers functions, which indicate unpolarized quark distributions in the transversely-polarized nucleon. For example, they appear in single spin asymmetries of hadron-production processes $p + \vec{p} \rightarrow h + X$. Their measurements are valuable not only for understanding transverse structure but also for finding a relation to semi-inclusive lepton measurement because the TMD distributions change sign due to a difference of the gauge link. It is analogous to the Aharonov-Bohm effect.[10] In order to show the advantage of J-PARC measurements, we show single spin asymmetries of D-meson production at J-PARC and RHIC by considering the Sivers' mechanism in Fig. 9.[5,11] The figures indicate the advantage that the quark (gluon) Sivers functions are determined well at J-PARC (RHIC).
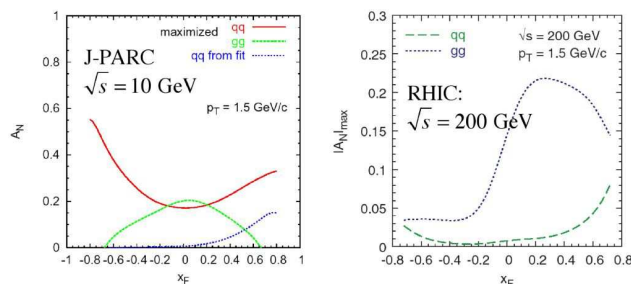

Fig. 9.   Single spin asymmetry in D-meson production at J-PARC and RHIC.[5,11]

3.3.1. *Tensor-polarized parton distribution functions*

In spin-one hadrons and nuclei such as the deuteron, there exist new structure functions in charged-lepton deep inelastic scattering, and they are called b_1, b_2, b_3, and b_4. The twist-2 structure functions are b_1 and b_2, and they are expressed in terms of the tensor-polarized quark distributions $\delta_T q(x)$. The b_1 was first measured by the HERMES collaboration; however, the detail of x dependence is not clear and there is no accurate data at

Fig. 10.   Tensor-polarized PDFs.[12]

medium and large x. The JLab b_1 proposal was approved and its measurement will start in a few years. The HERMES data indicated the violation of the sum rule $\int dx b_1(x) = 0$,[12] which suggests the existence of finite tensor polarization in antiquark distributions. This finite $\delta_T \bar{q}(x)$ can be directly measured at hadron facilities by Drell-Yan processes with tensor-polarized deuteron $(p + \vec{d} \rightarrow \mu^+ \mu^- + X)$.[12] We note that the polarized-proton beam is not needed for this experiment. This experiment is complementary to the HERMES and JLab measurements of b_1 in the sense that the antiquark tensor polarization can be measured specifically. The experiment will clarify an exotic dynamical aspect of the deuteron in terms of quark and gluon degrees of freedom, which cannot be done in low-energy measurements.
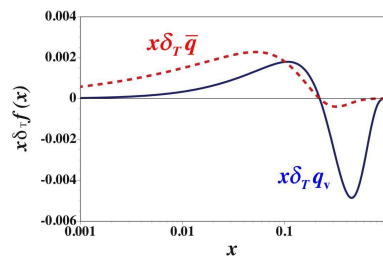
3.3.2. *Elastic single-spin asymmetry*

The origin of the nucleon spin is one of unsolved issues in hadron physics; however, there is another mysterious experimental result in elastic spin symmetries. For example, measurements indicated that the single-spin asymmetry in $p\vec{p}$ increases as $p_\perp$ becomes larger at AGS in Fig. 11.[13] According to perturbative QCD, the asymmetry has to vanish at $p_\perp \to \infty$. Because the data are taken up to $p_\perp^2 = 8$ GeV^2, nonperturbative physics might have contributed to the finite asymmetry. Considering the peculiar feature of the AGS data, we need to confirm the experimental measurements by an independent facility such as J-PARC before discussing possible physics mechanism. However, rather than a mere confirmation, innovative methods should be developed, such as by changing targets and by considering angular distributions in order to provide clear evidences for theorists to understand the mechanism.
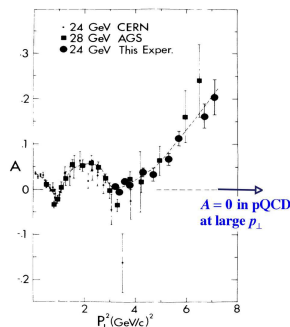

Fig. 11.   Elastic single spin asymmetry in $p\vec{p}$.[13]

3.4. *Spin physics with proton-beam polarization*

It is technically possible to polarize the primary proton beam at J-PARC.[5] However, it requires a major update of the facility, we need to propose significant projects which are worth for the investment. As shown in Fig. 4, J-PARC could measure structure functions in the medium-x region $0.2 < x < 0.7$, whereas RHIC probes a smaller-x region ($x \sim 0.1$). In order to determine all the partonic contributions to the nucleon spin,

Fig. 12.   Situation of polarized PDFs.[14]

the polarized PDFs need to be precisely understood from small x to large x, namely from the RHIC region to the J-PARC one. Therefore, it is a complementary facility to RHIC and other high-energy accelerators. Although longitudinally-polarized PDFs become clearer recently by various hadron and lepton reactions as shown in Fig. 12, their flavor decomposition and gluon distribution are not obvious yet. If the proton beam is polarized with the designed energy 50 GeV, the J-PARC facility could significantly contribute to the clarification of the origin of the nucleon spin.
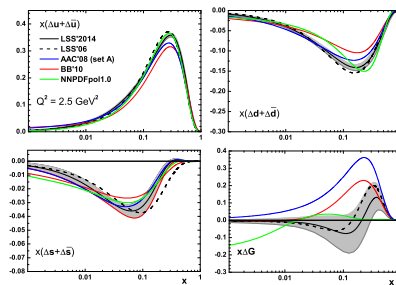
In addition, there is new transverse spin physics, such as twist-two transversity distributions, by measuring double spin asymmetries of Drell-Yan processes with transversely polarized protons. The quark transversity distributions are unique in the sense that they do not couple to the gluon polarization due to their chiral-odd property. They are very different from the longitudinally-polarized PDFs. The transversity distributions can be measured at medium x with the polarized proton beam at J-PARC.

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4. Summary

A wide range of spin projects are possible in particle and nuclear physics at J-PARC. As the particle-physics topics, we introduced muon $g-2$, muon and neutron electric dipole moments, and time-reversal violation experiment in a kaon decay. They could probe physics beyond the standard model by precision measurements with the high-intensity advantage of the J-PARC facility, and the measurements should shed light on new physics direction. In hadron spin physics, the studies of GPDs and TMDs should clarify the origin of the nucleon spin and also the three-dimensional structure of the nucleon including the transverse structure. In particular, the high-momentum beamline will be ready soon, and it can be used for various topics on high-energy hadron spin physics.

Acknowledgments

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